

# COAXIAL RING CYCLOTRON AS A PERSPECTIVE NUCLEAR POWER ENGINEERING MACHINE

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## Abstract

The circuit arrangement of the proposed coaxial ring cyclotron (CRC) is described, and its main advantages, such as simple injection technique, several injected beams summation option, high efficiency, are considered. The proposed proton accelerator is a perspective machine for the solution of the main problems of the present day nuclear power engineering as well as for the next-generation nuclear power plants, representing a combination of subcritical reactors and particle accelerators. The possibility of installation of CRCs into ring accelerators with an average diameter from 60 to 100m, e.g., the Yerevan electron synchrotron, is considered.

## Introduction

In recent years a complex of major applied problems has clearly crystallized, for successful solution of which are required powerful proton accelerators with proton beam intensity from 5 to 100mA, energy from 500 to 800 MeV, and high efficiency. To such problems relate, e.g., production of different radioactive isotopes, turning nuclear fuel out from  $U^{238}$  and  $Th^{232}$ , nuclear power plant radioactive waste treatment, designing of safe (subcritical) and next-generation waste-free nuclear power plants, which can utilize unenriched uranium or thorium. As well as in this connection, due to the successful conduction by C. Rubbia's group, CERN [1] of the experiment approving in principle a new and perspective possibility

of nuclear power production using proton beams and a subcritical reactor, the development of appropriate accelerators becomes an urgent necessity.

### Comparison of Known-Type Accelerators

Leaving the consideration of new acceleration techniques, let us dwell on traditional machines, such as *cw* linacs and isochronous cyclotrons, suitable for the goals mentioned. Linac projects are developed mainly in the USA, while isochronous cyclotrons in West Europe and Russia, the reason being probably connected with the achievements of these countries in the relevant fields of accelerator engineering.

A comparative analysis of these two types of accelerators has been done in [4,5]. The main drawback of linacs is that for a given beam the accelerating system is used only once, which is not the case with a cyclotron, where it is used many times. This inevitably increases sharply the power of losses, which, e.g., for such mesonic factories reaches  $40 - 50 MW$  in pulse [2]. In case of continuous operation of such linacs, the power of losses will essentially affect the overall efficiency which is one of the decisive factors in designing commercial models. There are also other considerations discussed in details in [3,4,5].

To the drawbacks of the cyclotron-type accelerators relate the complexity of injection and summation of several beams, and the earlier problem of  $\approx 100\%$  extraction of powerful megawatt beams, which caused in some projects the preference to be given to linear accelerators [5]. Later, however, the beam extraction problem was successfully resolved theoretically [6] with a following experimental verification [7] realized in the isochronous cyclotron SIN-PSI VILLIGEN, Switzerland, having record parameters to the present day:  $E = 590 MeV$ ,  $I = 1.0 - 1.5 mA$  [3,13]. But the problem of several beams summation and injection into a cyclotron still remains open. By the way, the problem of summation of, to our regret, only two beams has been successfully resolved for linacs, by creating the "FUNNEL" system suggested by B.Montague and K.Bongardt [8,9], which has been tested at LANL [10]. In the present paper is considered a method of solution of that problem for cyclotrons, proposed by one of the coauthors (Tumanian A.R.).

### Coaxial Ring Cyclotron

It is known, that the proton beam injection path usually passes from above or from below of the magnetic system of any type of cyclotrons. Then with the help of a group of bending

magnets, the protons are transferred onto the median plane and then with the help of a system of magnetic and electrostatic deflectors are injected into the ring-shaped chamber. In such a bulky arrangement, it is problematic to organize a simultaneous injection and summation of two or more beams.

It is suggested to increase the diameter of the isochronous ring cyclotron so, that it becomes possible to place in its central part several injectors (cyclotron or other type, see Fig.1) in a coaxial arrangement. At such an arrangement, it obviously becomes easier to inject several beams into the same ring, into different by radius orbits. So, let us name the new method proposed as "orbital" method of filling the ring up with beams.

Orbital filling of the cyclotron ring is provided by the fact, that the energy of each injector differs from that of the next one by  $\Delta E_{\text{inj}}^i$ , the conditions of separation of different injected bunch orbits being met:

$$\sum_{i=1}^m \Delta E_{\text{inj}}^i < \Delta E_{\text{cycl}}; \quad m[A + r(\Delta E/E)] < \Delta R_{\text{cycle}},$$

where  $r(\Delta E/E)$  is "orbit width",  $A$  is amplitude of betatron oscillations,  $\Delta R_{\text{cycl}}$  is radial gain per turn,  $\Delta E_{\text{cycl}}$  is energy gain per turn,  $\Delta E/E$  is energy spread,  $m$  is number of injectors. All " $m$ " beams can be extracted from one or different outlets on the ring, the number of outlets not exceeding the number " $m$ ".

The average radius of the final orbit is chosen with account of the following considerations. On the one hand, the machine's diameter as well as the magnetic poles width do increase with orbit's radius, this increasing capital outlays. But on the other hand, larger radius leads to desirable decreasing of " $B$ " induction in cyclotron magnets, this making it possible to exclude the main power supply system of magnets. Such a possibility arises at less than 3.0 kGauss induction in magnets.

In this case, it is possible to use cast permanent magnets made of hard magnetic materials (Alnico, Magnico, etc.). Such magnets have practically unrestricted forms and sizes and are widely used in powerful klystrons, magnetrons, etc. [12].

Important is the fact, that exclusion of the main power supply system of magnets leads to an obvious and essential improvement of cyclotron overall efficiency, as the power of such power supply systems makes hundreds of kilowatts, e.g., 650kW for SIN (at  $E = 590\text{MeV}$ ,  $I = 0.1\text{mA}$ ) at a total power consumption of 1500kW[13]. So, at exclusion of the power

supply system, the cyclotron's efficiency will improve more than 1.7 times , this essentially shortening the pay-back period.

### The YerPhI Version of CRC

The basic parameters of the Yerevan Physics Institute version of CRC are:  $R_m = 34.5m$ ; tunnel width  $-6.0m$ ; thickness of tunnel walls  $-3.0m$ ; inner diameter -  $57m$ . Six SIN-type cyclotrons serve as injectors, each with  $15m$  diameter,  $E_{inj} = 500MeV$ ,  $I=1.5mA$ . Assuming, that CRC has 48 acceleration gaps, 32 of which are occupied by SIN-type resonators, the energy gain per turn will make  $\Delta E_{cycl} = 16MeV$ , the radial gain per turn at the injection level making  $\Delta R_{cycl}^{inj} \cong 26cm$ . The average radius  $R_{500} = 32.5m$  for particles with  $E_{inj} = 500MeV$ , and the working area (magnetic poles width) should not exceed  $\Delta R_{mag} = 3.7m$ . Then it is easy to notice, that in such a ring with a final radius of  $R_{fin} = 36.1m$  the protons can be accelerated up to  $E_{fin} = 800MeV$ . The average value of induction in magnets will vary with energy between  $1.117 \div 1.352kGauss$ .

Note, that the form of magnets and the field topography, spirality, variation depth, etc. should be defined with account of axial betatron oscillations stability conditions.

Suppose the injected beam radial size, equal to the amplitude of betatron oscillations in CRC,  $A = 1cm$ , and energy spread  $\Delta E/E_{inj} = 10^{-3}$ , then from six different SINs, there can be injected into the cyclotron magnetic ring beams with an energy increment of  $\Delta E_{inj}^i = 2.5MeV$ , providing a complete separation of beams. The value of  $\Delta E_{inj}^i$  will remain unchanged at a correlational change of beam injection parameters, e.g., at  $A = 0.5cm$  and  $\Delta E/E_{inj} = 2 \times 10^{-3}$ .

Simple calculations show, that with the particle energy increasing from 500 to 800MeV, the radial gain per turn decreases from  $\Delta R_{cycl}^{inj} = 26.2cm$  down to  $\Delta R_{cycl}^{inj} = 13.8cm$ . Nevertheless, all six beams will be spaced, as far as in the process of acceleration, both the betatron oscillation amplitude and energy spread decrease, this narrowing the regions occupied by beams.

On the basis of the PSI cyclotron update results, the global efficiency of the three-stage cyclotron complex (regular 900MeV machine,  $I = 10mA$ ) is estimated to be 40%[14]. Assuming the same efficiency as minimum for the YerPhI version of CRC combined with a

subcritical thorium reactor [14], it would be possible to produce a useful electrical power of more than 70MW.

### **Conclusion**

The scientific and technical solutions and preliminary estimations, the results of which are presented in this report, would be sufficient to start numerical calculations of different versions, simulation of the basic systems and units, and develop a tentative CRC version. The purpose of the present report is to show there are no restrictions for creation of a CRC, which economically prevails over its counterparts.

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